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3.36-Tbit/s OAM and Wavelength Multiplexed Transmission over an Inverse-Parabolic Graded Index Fiber

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Abstract: We demonstrate MIMO-free two-dimensional multiplexing, transmission and de-multiplexing over 4 OAM modes (including two modes of $|l| = 2$) and 15 wavelengths through 100-meter inverse-parabolic graded-index fiber with aggregated total capacity of 3.36-Tbit/s.
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1. Introduction

Orbital angular momentum (OAM) of light has been intensively investigated recently in the optical communications community, as it provides large and accessible modal space for achieving high system capacity and spectral efficiency through OAM-based mode division multiplexing (MDM) [1, 2]. However, the implementation of channels with higher-order OAM modes in transmission links is still facing difficulties due to the restrictions brought by techniques of OAM-mode MUX/DeMUX, crosstalk (XT) equalization, etc. Therefore, despite of the fact that fibers supporting propagation of up to 22-36 OAM modes over short distances have been reported [3, 4], the state-of-the-art in OAM fiber communications is reported only with the lowest order OAM modes ($l = \pm1$) and fundamental mode ($l = 0$) [1, 5, 6]. Recently, the inverse-parabolic graded-index fiber (IPGIF) developed by Ung et al. is proposed for the transmission of OAM modes with order up to $|l| = 2$, with a large modal index separation $\Delta n_{eff} > 2.1\times10^{-4}$ to suppress the XT between non-degenerate modes [7]. In this paper, we report the 3.36-Tbit/s MIMO-free transmission of 28 Gbaud QPSK signals through a 100-meter IPGIF over a two-dimensional multiplexed channel space consisting of 15 wavelength channels each carrying 4 multiplexed OAM modes, including two OAM modes of group $|l| = 2$ and two mode of $l = 0$ (OAM_{+2R}, OAM_{-2L}, OAM_{0R}, OAM_{0L}). To the best of our knowledge, this is the first demonstration of an OAM-MDM transmission system employing higher order OAM modes ($l > 1$).

2. Experimental setup

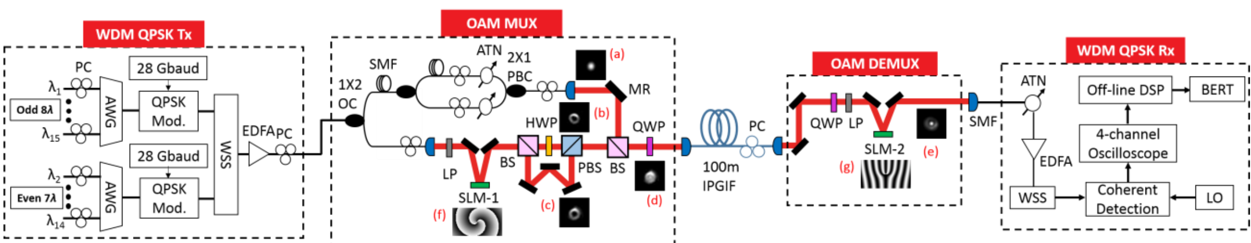

Fig. 1. Experiment setup of the transmission system. Insets (a)-(c): mode profiles of OAM_0, OAM_{+2} and OAM_{-2}; (d) profile of the four multiplexed modes; (e) de-multiplexed mode OAM_{+2R}; (f)-(g): phase patterns for 'perfect' vortex generation and de-multiplexing.

Figure 1 shows the experiment setup of the 3.36-Tbit/s transmission system. At the transmitter side, the odd and even channels of 15 wavelengths (from 1547.3 nm to 1552.9 nm, spaced 50 GHz) are modulated by two FPGA-driven 28 Gbaud QPSK modulators, respectively, and then inter-leaved with a multiport wavelength selective switch (WSS). All modulated channels are amplified by an Erbium-doped fiber amplifier (EDFA) and separated into two branches with a 1X2 optical coupler (OC). The first branch of light is delayed with a 100-meter single-mode fiber (SMF) for decorrelation, and then equally divided again. Two polarization controllers (PC) are used to generate two orthogonally linear-polarized fundamental modes, and a polarizing beam combiner (PBC) is used for these two modes to be launched together with a single collimator. The second branch is collimated, polarized with a linear polarizer (LP) and reflected by a phase-only spatial light modulator (SLM) for conversion to OAM mode of $l = +2$. On SLM-1, the technique of 'perfect' optical vortex generation is applied [8]. The generated mode of $l = +2$ is again equally divided into two portions with a beam splitter (BS): one of the beams is reflected with an odd number of mirrors (MR) to reverse the OAM order as $l = -2$, and the polarization of the other is rotated by $\pi/2$ with a half-wave plate (HWP). These two orthogonally linear-polarized OAM modes with opposite orders are then recombined with a polarizing beam splitter (PBS), and then combined with the $l = 0$ mode. A quarter-wave plate (QWP) is used to convert the combined four modes into left- and right-hand circularly polarized to match the OAM eigen-modes in fiber (OAM_{0R}, OAM_{0L}, OAM_{+2R}, OAM_{-2L}). The overall losses (including in- and out-coupling and transmission in fiber) are around 2.7 dB and 6.3 dB for $l = 0$ and $|l| = 2$ modes, respectively. A PC is used on IPGIF at the output end to equalize the polarization mode dispersion (PMD) and mitigate the XT between degenerate modes OAM_{+2R} and OAM_{-2L}, and while another one is used on SMF after PBC for $l = 0$ modes [9]. In this experiment, $|l| = 1$ modes are not used because of the high PMD between even and odd HE_{21} modes [6] and strong interactions from nearby TE_{01} and TM_{01} modes. Attenuators (ATN) are used on $l = 0$ channels to equalize the power of all modes in fiber for balanced OSNR. After transmission in fiber, SLM-2 is used to de-multiplex modes of different orders. The WDM channels carried on each OAM mode are filtered with a WSS for coherent detection and bit-error rate test (BERT).

3. Results and discussions

In Figure 2(a), the measured BER curves as a function of OSNR for the back-to-back (B2B) case and for all four OAM modes at 1549.7 nm are plotted. BER measurements for three cases are performed to identify the penalty sources, including w/o XT (with one wavelength and one mode), w/ OAM XT (with one wavelength and all four modes), and w/ all XT (with all 15 wavelengths and all four modes). At the BER of 3.8×10^{-3}, the average power penalties of the four modes for the cases of w/o XT, w/ OAM XT, and w/ all XT are 1.4 dB, 6.3 dB and 8.2 dB, respectively. Figure 3(b) illustrates the multiplexed 15 wavelengths. Figure 3(c1) to (c4) show the constellations of 28 Gbaud QPSK for the de-multiplexed mode OAM_{-2L} w/ all XT at the BER of 1×10^{-6}, 2×10^{-4}, 1×10^{-3}, and 2×10^{-2}, respectively. In Figure 3(d), the BER of all four modes over the 15 WDM channels are shown, and all 60 channels can achieve a BER of $< 2.4\times10^{-2}$ (SD-FEC limit). The variation of BER with wavelength is primarily attributed to the dispersive coupling between degenerate OAM modes induced by OAM-PMD [9]. Besides, the system is optimized at around 1550 nm, and slight offset ($< 1\ \mu$m) at the IPGIF coupling section is created to induce additional modal coupling when the wavelength is tuned away, due to the dispersive response of SLM and other components. This issue can be potentially addressed in future with the developments in integrated OAM mode MUX/DeMUX technologies [10].

Overall, a total capacity of 3.36-Tbit/s is achieved with 60 MDM-WDM channels (4 OAM modes and 15 wavelengths) and 28 Gbaud QPSK signal on each channel without MIMO processing for MDM XT equalization. This work demonstrates the unexploited capacity potential of OAM fiber communications in higher order mode ($|l| > 1$) space, and the system capacity can be further expanded with the advances in OAM fiber technologies.

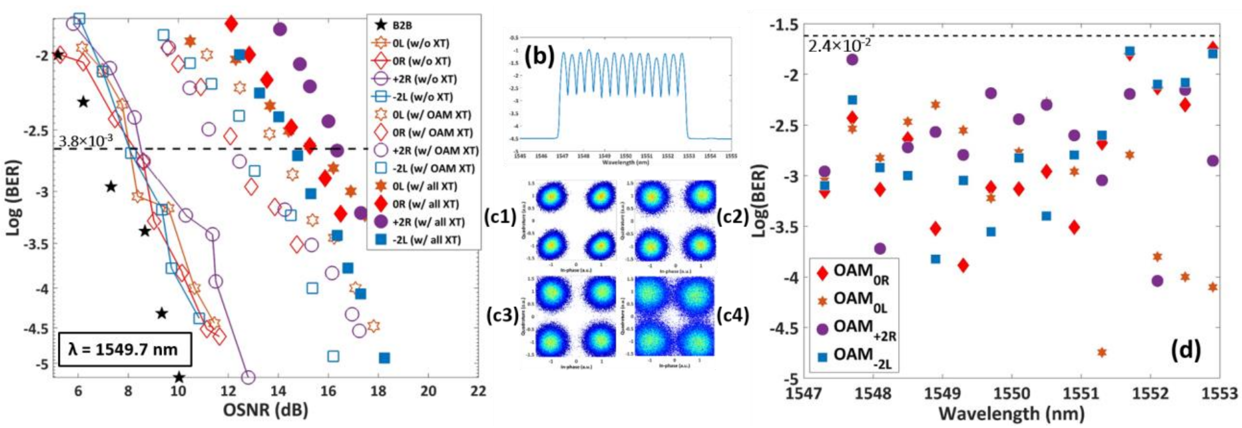

Fig. 2. (a) BER vs. OSNR for B2B and the four OAM modes at 1549.7 nm; (b) multiplexed 15 wavelength channels; (c1) to (c4) constellations of QPSK signals for de-multiplexed mode OAM_{-2L} (w/ all XT) at various BER levels; (e) BER vs. wavelength for all modes.

4. Acknowledgement

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